Copper demand, supply, and associated energy use to 2050

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ACKNOWLEDGEMENTS

We thank the United Nations Environment Programme, the US National Science Foundation, BP International, General Electric Global Research Center, and Shell Global Solutions, for useful comments and financial support.

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Abstract

To a set of well-regarded international scenarios (UNEP's GEO-4), we have added consideration of the demand, supply, and energy implications related to copper production and use over the period 2010-2050. To our knowledge, these are the first comprehensive metal supply and demand scenarios to be developed. We find that copper demand increases by between 275-350% by 2050, depending on the scenario. The scenario with the highest prospective demand is not Market First (a "business as usual" vision), but Equitability First, a scenario of transition to a world of more equitable values and institutions. These copper demands exceed projected copper mineral resources by mid-century and thereafter. Energy demand for copper production also demonstrates strong increases, rising to as much as 2.4% of projected 2050 overall global energy demand. We investigate possible policy responses to these results, concluding that improving the efficiency of the copper cycle and encouraging the development of copper-free energy distribution on the demand side, and improving copper recycling rates on the supply side are the most promising of the possible options. Improving energy efficiency in primary copper production would lead to a reduction in the energy demand by 0.5% of projected 2050 overall global energy demand. In addition, encouraging the shift towards renewable technologies is important to minimize the impacts associated with copper production.

Keywords: Copper, Resources, Energy, Scenario Analysis, Dynamic modelling

1. Introduction

Copper is one of the most widely-used metals in society. Due to its unique properties copper is essential for several economic sectors, including infrastructure, wiring, plumbing, transportation, and consumer and industrial electrical and electronic equipment (EEE). In recent years, the demand for copper has grown rapidly (USGS, 2009) as a result of the increasing global population, economic growth (especially in emerging economies), and the transition to a more sustainable society. This growth in copper demand is higher than the increasing supply of copper from secondary resources, explaining the growing demand for primary copper (ICSG, 2006, cited in Gomez et al., 2007; ICSG, 2012 and 2015). This has raised concern regarding the future availability of copper and its companion metals including tellurium, selenium, silver, cobalt, and molybdenum, which are necessary for construction activities as well as for the transition to sustainable energy, transportation, and industrial systems (Elshkaki and Graedel, 2015; Nassar et al., 2012, 2015).

In addition to resource availability concerns, there is increasing concern related to the energy requirement to produce metals and to the associated environmental impacts. The mining industry is one of the most energy-intensive industrial sectors, and thus one of the largest contributors to global CO_2 emissions. This is mainly due to the amount of metals produced and the low concentration of most metals in ore deposits, which led to the mining of large quantities of the ore. The global energy consumption for the principal primary metals (iron, aluminum, copper, manganese, zinc, lead) has increased from 32 EJ/y in 2007 to 52 EJ/y in 2012 (Norgate and Jahanshahi, 2011), which is about 10% of the total 2012 primary energy production (Fizaine and Court, 2015). Copper is one of the metals whose production is highly energy intensive, and consequently has high environmental impacts. In Chile, the world's largest copper producing country, the copper industry is by far the largest energy consumer and the largest GHG emitter (Alvarado et al., 2002). As the demand for copper increases, its ore grade is expected to decrease, and the energy required for copper production and the related CO_2 emissions are thus expected to increase fairly rapidly (Ayres, 2001; Kuckshinrichs et al., 2007; Mudd, 2010; Northey et al., 2014; Valero and Valero, 2014).

Several studies have attempted to assess the future demand for a number of different metals (Allwood et al., 2010; Elshkaki et al., 2005; Elshkaki and van der Voet, 2006; Gerst, 2009; Halada et al., 2008; Hatayama et al., 2010; Kleijn and van der Voet, 2010 (who find a potential supply limitation for copper due to renewable energy deployment); Liu et al., 2012; Pauliuk et al., 2012; Stamp et al., 2014; Van der Voet et al., 2002; Van Vuuren et al., 1999). However, these metal demand scenarios tend to be limited to a focus on specific technologies rather than on more general uses. In addition, none follow from a foundational set of scenarios generated by specialists in such disciplines as demography, economics, and assessments of industrial limitations and opportunities. Thus, there remains a need for scenario approaches to metal futures that emphasize breadth in the choice of metals and employ a widely recognized family of scenarios as a starting point.

In the present study, we develop four scenarios for the global demand for copper, the global and regional supply of copper, and the energy required for primary and secondary copper production. The foundation for these metal scenarios is the Fourth Global Environmental Outlook (GEO-4) set of scenarios of the United Nations Environment Program, which are based on the Global Scenario Group (GSG) approaches and related scenarios (Bakkes et al., 2004; Electris et al., 2009; Kemp-Benedict et al., 2002; UNEP, 2007). A detailed discussion of the GEO scenarios and comparison with other scenarios can be found in Raskin et al., 2005 and Van Vuuren et al., 2012. The GEO-4 scenarios, termed Market First (MF), Policy First (PF), Security First (SF), and Equitability First (EF), are briefly described in Box 1. Each includes global and regional projections of population, per capita income, and source-specific energy demand. These well-vetted scenarios have been extensively employed in the past at global and regional levels to examine possible futures of such variables as atmospheric emissions, food availability, water withdrawals, and species abundance changes (UNEP, 2006, 2007, 2010; Van Vuuren et al., 2012). To those scenarios we add copper-relevant technology demand, primary and secondary copper supply, and related energy use. The period of study is 2010-2050, with one year time resolution.

2. Methodology

2.1 Copper demand

Regression analysis is used in many scientific fields as a statistical tool to estimate and analyze the relation between a dependent variable and a number of independent, explanatory variables. It identifies the variables that are significant and that contribute the most to the dependent variable. The approach further examines the separate and combined effects of significant variables. The optimal regression model, the adequacy of the model, and the significance of the variables are traditionally described by several statistical parameters: the coefficient of determination (R^2), the adjusted coefficient of determination (R^2adj), and the t- and F- statistics.

We carried out the analysis of the historical demand for copper from 1980 to 2010 using regression analysis with per capita GDP, the level of urbanization, and time as explanatory variables. Time is used as a proxy for such time-dependent variables as policy changes, substitution, and technological development. The form of the regression equation is

$$Y(t) = \alpha_0 + \sum_{i=1}^{n} \alpha_i X_i(t) + \varepsilon(t) \qquad (1)$$

where *Y(t)* is the inflow of metals into the stock-in-use at time t, n is the number of explanatory variables, $X_i(t)$ are the explanatory variables at time t, α_i are the regression model parameters and $\varepsilon(t)$ is the residuals of the regression model.

The linear regression model is used in this analysis to find the optimal model for the total historical demand for copper and its use in each major copper-relevant industrial sector. Data for the total demand for copper and its demand in nine sectors is estimated based on information collected from different sources and shown in Figure 1(a) (USGS, various years; Spatari et al., 2005; Nassar et al., 2012). GDP/capita is estimated using GDP at purchasing power parity (constant 2005 international $) and population records from the World Data Bank (World Bank, 2015). The level of urbanization, which represents the share of inhabitants living in urban areas as per cent of total population, is also estimated using World Data Bank population records, together with urban ratios from the United Nations World Urbanization Prospects (World Bank, 2015; UN, 2015).

It is, of course, true that if and when a resource of any kind becomes scarce, its price is likely to rise rapidly and demand would thereby decrease accordingly. In the case of copper, a decrease in demand would likely result in an inability to respond efficiently to the needs for the services that copper provides, such as efficient conductance of electricity. All such demand-supply-economic systems are demonstrably non-linear, and some researchers (e.g., Sverdrup et al., 2014) have attempted to model metal futures in a non-linear fashion. In the absence of a firm basis from which to specify such non-linearities, however, we choose instead to model copper demand as a function of widely-regarded expert assessments of likely population growth, per capita income, and level of urbanization under different types of global development (see above). Time is included as an additional variable to capture other possible historic variables such as substitution, technological development and policy changes. We then compare the demand results to detailed predictions of primary and secondary copper supply to identify situations in which future demand may or may not be able to be met by available supply, and to identify the implications of declining ore grade and enhanced energy demand.

2.2 Copper supply

The demand for copper is met by the supply from primary and secondary (recycled) sources. The historical supply of copper from secondary sources and its contribution to total copper demand are shown in Figures 1(b) and 1(c) (ICSG, 2006, cited in Gomez et al., 2007; ICSG, 2012, 2015). The fraction of copper demand that can be met by the supply from secondary sources is determined by the historical copper demand, the lifetime of copper applications, and copper recycling rates and efficiencies. Although the recycling rate of copper and the supply from secondary sources may increase over time, the fraction of copper demand that could be covered by these sources has decreased from about 17.5% in 1980 to 12.5% in 2005 and slightly increased afterwards reaching about 17.5% in 2014 (ICSG, 2006, cited in Gomez et al., 2007; ICSG, 2012, 2015). This is mainly due to strong increases in the demand for copper, together with the long lifetime of copper applications. We conservatively estimate the fraction of demand covered by secondary resources to be 17.5% in the four scenarios. The supply of copper from primary sources in the future is estimated based on the total demand for copper in each scenario, less the supply of copper from secondary sources.

The supply of copper from primary sources is met by copper production in a number of countries. As shown in Figure 1 (d), the production of copper has historically been dominated by the production in Chile (21.5% of world cumulative production) and in the USA (18.5%), while in recent years the Chilean fraction has increased (34% of world production in 2007-2012) (USGS, various years). Two measures of mineable copper that have been widely used are the "reserves" (amounts in deposits currently economic to mine) and the "reserve base" (sub-economic amounts in deposits, plus the reserves (McKelvey, 1972; Grace, 1984). In terms of potentially realizable copper, Chile has the largest Reserves and Reserve Base (28% and 34% respectively), followed by Peru (13% and 11%), Australia (12.5% and 8%) and the United States (5% and 7%) (USGS, various years). A detailed assessment of copper Ultimately Recoverable Resources (URR) on a global level and in each of the producing countries has been published by Northey et al. (2014), based on Mudd et al. (2013). The URR is an estimate of the total copper that society has recovered plus what it can be expected to recover from mineral deposits; it turns out to be about 1.7 times the Reserve Base estimated by the USGS (2009). As mining moves past the reserve base into the URR ore grades will decrease, potentially hitting the "mineralogical barrier" at about 0.1% ore grade (Skinner, 1976). The challenges of energy and water demand and of waste rock disposal at these poorer ore grades are thought to preclude the use of such rock resources rather than the richer ore resources as a source of copper (Gordon et al., 1987).

The shares of individual countries in the cumulative production of copper up to 2010, the average copper production between 2007 and 2012, copper reserves and reserve base, and copper URR and RR are shown in Figure 1 (d). In our work we carried out two analyses for the copper supply. The first is based on the copper reserve base and assumes that the future share of copper supply by each of the producing countries is the same as its average share in production between 2007 and 2012. The second is based on the RR estimates and assumes the future share in the supply by each of the producing countries is the same as its share in the cumulative production up to 2010.

2.3 Energy required for copper production

The total amount of energy required for copper production in each scenario is the amount of energy needed to satisfy copper demand using both primary and secondary resources. It has been reported that the production of copper from primary sources requires between 30 and 90 MJ/kg and the energy saving of recycling between 84% and 88% (UNEP, 2013). Based on these numbers, the energy required for copper production from secondary sources would be between 4.2 and 12.6 MJ/kg, with an average value of 8.4 MJ/kg. It has been also reported that copper production from secondary sources requires 6.3 MJ/kg (Grimes et al., 2008) and 14.9 MJ/kg (Nuss and Eckelman, 2014). The future energy required for copper production from secondary sources is assumed to be 8.4 MJ/kg.

The energy required for the production of copper from primary sources is mainly consumed in the mining and mineral processing stage. It is reported that 18% of the energy required for copper production is related to copper mining, 42% to concentrating, 27% to smelting, 7% to refining, and 3% to tailings impoundment (Kennecott Utah Copper, 2004). A more recent study based also on industrial sources (Norgate and Jahanshahi, 2010) reports that, depending on ore grade, the mining and mineral processing stages together account for 60% to 90% of the total energy required to process copper from ore to product. Going forward, the total amount of energy required to produce copper from primary resources will be determined by the future ore grade, energy efficiency, and the process used in copper production. As shown in Figure 2 (a), the average copper ore grade is expected to decrease in the future as a function of cumulative production. The relation between the ore grade and cumulative production used in this study is given in Eq. 2 (based on Mudd, 2013; Schodde, 2010; USGS, 2013).

$$g(t) = 1.88e^{-1.13 \bullet 10^{\wedge}-9Q(t)} \qquad (2)$$

where *g(t)* is ore grade (per cent) and *Q(t)* is cumulative production over time.

The anticipated decrease in ore grade will lead to an increase in the energy required per ton of produced copper, mainly in the mining and mineral processing stage (Figure 2 (b); Norgate and Jahanshahi, 2010). The future energy required for primary copper production is then estimated by Eq. 3a and 3b. We assume that 80% of copper is produced by the pyrometallurgical process and 20% by the hydrometallurgical process (Norgate and Jahanshahi, 2010).

$$E_{pyro}(t) = 199e^{-0.67 \bullet g(t)} \qquad (3a)$$

$$E_{hydro}(t) = 264e^{-0.61 \bullet g(t)} \qquad (3b)$$

The two equations (3a and 3b) are based on the data review and compilation of Norgate and Jahanshahi (2010). Data from specific copper processing sources might give different estimates for the energy required as a function of ore grade (see, for example, Valero and Valero, 2014) and by production process locations.

In contrast to energy increases due to decreasing ore grade, and thus to increased processing of waste rock, the energy required per ton of produced copper is expected to diminish as a result of increasing energy efficiency. It has been shown that the actual energy used in the extraction of several metals is 3-25 times more than the theoretical energy required (Norgate and Jahanshahi, 2010); this may indicate an opportunity for reducing the amount of energy required per ton of metal produced (but only if ore grade does not decline precipitously). It is also reported that the difference between theoretical and actual energy required for copper production in Chile, the main copper producer, is high and that there is a large potential for the reduction in the energy use and the modification of the fuel mix in the Chilean copper industry (Alvarado et al., 1999; Alvarado et al., 2002). The potential energy saving at different stages of copper and other metals production is 10% to 60% (Norgate and Haque, 2010). An overall potential energy saving of 30% by 2050 has been assumed in this study as a midpoint among these estimates and predictions.

3. Results and discussions

3.1 The historical demand for copper

We analyzed the historical demand for copper in different industrial sectors using regression analysis with per capita GDP, the level of urbanization, and the time as explanatory variables and found that each one of these variables is significant when used individually (Tables S1-S7 in the Supplementary Information). However, the most significant variable in explaining the total demand for copper and its demand in different sectors on a global level is the per capita GDP, in accordance with the results of Binder et al., 2006. The correlations with per capita GDP also have the highest R^2. When per capita GDP is combined with the level of urbanization, the R^2 for the correlations is either similar to those of the correlations with the individual variables or slightly higher. When per capita GDP is combined with the time variable, the R^2 for the correlations is either similar to those of the correlations with the individual variables or slightly higher. For some industrial sectors, the time variable and per capita GDP are significant, while for others the only significant variable is the per capita GDP. When the level of urbanization is combined with the time variable, both are significant and have the expected sign, however, R^2 for the correlations is either similar or lower than those associated with the correlations when the per capita GDP and the time are combined. When the three variables are combined in one relationship, the time and the level of urbanization are not significant. The best correlations between the total copper demand and its demand in different sectors, and the explanatory variables that are used in the estimates of the future demand in the four scenarios, are listed in Table S8 of the Supplementary Information. The most significant variable in explaining the demand for copper in infrastructure, plumbing, and wiring is per capita GDP. For all other industrial sectors, the most significant variables are per capita GDP and time. The historical demand for Cu and its demand as estimated by the models obtained by regression analysis for each sector are shown in Figure S1.

3.2 The future demand for copper

The future demand for copper in different sectors is estimated using the equations obtained by regression analysis (Table S8) and the projections for per capita GDP and level of urbanization given by the GEO scenarios. The total demand for copper from 2010 through 2050, and its demand in the different sectors for the years 2010, 2025, and 2050 in the four scenarios are shown in Figures 3 (a) and (b). The total demand for copper in 2050 compared with that in 2010 is calculated to be 275% (MF), 275% (PF), 213% (SF), and 341% (EF). The infrastructure sector is the main end use sector for Cu, reaching 25%, 25%, 26%, and 24% of total copper demand by 2050 in the four scenarios respectively, followed by wiring (15%, 15%, 15.5%, and 14.5), industrial EEE (13%, 13%, 12%, and 14%), plumbing (10.5%, 10.5%, 11%, and 10%), built in appliances (10%, 10%, 9%, and 10.5%), consumer electronics (10.5%, 10.5%, 10%, 11%), and motor vehicles (8%, 8%, 9%, 7.8%). Overall, these results indicate the potential for 200-350% increases in copper demand over the next four decades. These are quite dramatic changes, and all scenarios would require very substantial increases in copper mining and processing, with consequential effects on the environment.

It is interesting that copper demand is highest in the EF scenario, where progress toward global equity requires significant metal increases to meet the needs of the global population. The demand in the main copper applications (infrastructure, wiring, and plumbing) is driven by per capita GDP, which is the highest in the EF scenario. Unless the use of metals is decoupled from per capita GDP, the EF scenario appears unlikely to be sustainable in terms of copper. In contrast, copper demand is lowest in the SF scenario, in which regional isolation and attendant income stagnation inhibits the growth in metal use. Copper demand in the MF scenario is the same as demand in the PF scenario, because the growth in per capita GDP on a global level is the same in the two scenarios. This will not be the case at the regional level, however, as the two scenarios assume different growth in per capita GDP for different regions. For example, in North America and Western Europe the per capita GDP in the PF scenario is less than the MF scenario, while in Africa, China, Middle East, and Latin America per capita GDP in the PF scenario is more than per capita GDP in the MF scenario. This leads to higher demand for copper in the PF scenario in the latter regions, especially for copper demand in the applications that are mainly determined by per capita GDP.

3.3 The future supply of copper

Copper demand is met by the supply from secondary sources and primary sources. The required future supply of copper from primary sources (demand minus secondary supply) is shown in Figure 3 (c), and from secondary sources in Figure 3 (d). These results assume that no limitations exist on copper ore deposits. However, such limitations do exist. Figure 4 shows the cumulative global copper production from primary sources compared to the Reserves, Reserve Base, Ultimate Recoverable Resources, and Remaining Resources. The figure shows that cumulative global copper production is expected to exceed its current reserves by about 2038 in the MF and PF scenarios, and by about 2040 and 2036 in the SF and EF scenarios. The cumulative production is expected to exceed the more expansive Reserve Base by 2048, 2048, and 2044 in the MF, PF, and EF scenarios respectively while it is not expected to exceed the Reserve Base in the SF scenario. Copper cumulative production is not expected to exceed the URR in the four scenarios. However, a risk of serious depletion of the URR around 2050 exists in the EF scenario.

The cumulative production from 2010 to 2050 in each of copper producing countries compared to their Reserve Base, as derived from a calculation that assumes that the share of individual countries in copper production in the future is the same as their average share between 2007 and 2012, is shown in figure S2. A similar calculation that assumes the share of individual countries in copper production in the future is the same as their average share in the cumulative copper production up to 2010 is shown in figure S3. In the first approach, only Australia, Mexico, Peru, and Poland do not exceed their RB in the MF, PF, and EF scenarios. In the SF scenario, Chile does not exceed its RB in addition to the countries listed for the other three scenarios. In the second approach, only Australia, Chile, China, Congo, Indonesia, Mexico, and Peru do not exceed their RR in the MF, PF, and EF scenarios. In the SF scenario, Poland does not exceed its RR in addition to the countries listed for the other three scenarios. All other countries are expected to exceed their RR at different times in the different scenarios.

3.4 Energy required for copper production

The energy required for copper production from primary sources is estimated based on the cumulative copper production in the four scenarios (Figure 5 (a)), the ore grade (Figure 5 (b)), the energy efficiency, and the energy required to produce one kg of copper by the pyrometallurgical and hydrometallurgical process routes. The resulting energy demand for the two process routes is shown in Figure 5 (c) and 5 (d), and the total energy required to produce all primary copper demanded in the four scenarios in Figure 5 (e). The solid lines in the figures represent the energy requirement based on the ore grade and energy relationship only, while the dashed lines represent the energy requirement including a reasonable increase in efficiency in the use of energy. The required energy for primary copper production in the four scenarios is 0.99% (MF), 1.43% (PF), 0.82% (SF), and 2.31% (EF) of the total final energy demand for all societal uses by 2050. If both primary and secondary copper production is considered, the total energy required is 1.00% (MF), 1.45% (PF), 0.83% (SF), and 2.33% (EF) of the total final fuel demand by 2050. These values are estimated based on a value of 8.4 MJ/kg for the energy required for copper production from secondary sources. If the other values of 6.3 MJ/kg or the 14.95 MJ/kg that have been reported by other studies (Grimes et al., 2008; Nuss and Eckelman, 2014) had been used, these estimates would change by only +/- 0.002% to 0.02%. These are dramatic numbers that could have a large impact on the global energy market, realizing that today the entire global mining and metals industry represents only about 10% of global energy demand (Fizaine and Court, 2015) and that the energy needed for present copper production is about 0.3% (Fizaine and Court, 2015). The highest amount of energy required is in the Equitability First scenario due to the associated high demand for copper and the low total global energy demand compared to the other scenarios. Although the energy required to produce copper is the highest in the EF scenario, this does not necessarily lead to the highest emissions of CO_2. This is because the EF scenario has the highest share of renewable technologies, with lower CO_2 emissions per unit of energy.

3.5 Discussion on the main driving factors in the model

Because these results are dramatic and potentially disruptive to the evolving global society, it is important to examine the credibility of the assumptions and driving factors in some detail. We do so here by addressing four aspects of the model: the appropriateness of the foundational scenarios and the exogenous variables related to copper demand, copper supply, and energy requirements for copper production.

The fundamental requirement for scenarios is not that they constitute accurate predictions, for that cannot be known, but rather that they are plausible ways in which change might occur. As such, the results of the scenarios provide the basis for considering the potential consequences should the results approximate actual situations over time. The Market First scenario essentially posits that the newly wealthy will wish to acquire possessions similar to those of the existing wealthy, and that market forces will enable that to happen. The Policy First scenario is similar except that government policies more respectful of renewable energy and the environment will be in force. The Security First scenario tilts toward confrontation rather than cooperation, with a consequent reduction in international commerce. Finally, the Equitability First scenario aims toward a more collaborative and inclusive world. Both because the foundational UNEP scenarios have been widely accepted and because all of the future visions outlined above seem plausible, our judgment is that the scenarios provide a reasonable foundation for this research.

Copper demand is strongly related to population and to per capita income, both of which are specified by the foundational GEO-4 scenarios. The proportion of copper deployed in various sectors of the economy inevitably assumes that today's copper-related teechnology will continue to be used during the 2010-2050 time period. Because copper is a resource that is widely employed, mostly to distribute energy, this seems a reasonable approach (although one could consider scenarios that incorporate alternative energy distribution technologies that are not now perfected or not widely deployed). As discussed by Raskin et al., (2005) and Van Vuuren et al., (2012), these scenarios have a relatively central position in terms of storylines and quantification among scenarios families, and their storylines are similar to those of other widely-used scenarios (e.g., GSG, IPCC SRES, WWV).

We recognize that a new technology that requires a new use for copper, or new research leads to a substitute for copper in existing technology, demand would need to be adjusted accordingly. For example, several recent studies have pointed out the possibility of substituting copper for silver in Si-based PV solar technology (García-Olivares, 2015; ITRPV, 2015). It is suggested by García-Olivares (2015) that 718,000 Mg of copper would be required to replace the silver needed for PV solar technologies if one-third of the 12 TW mean electric power required to sustain global energy demand is supplied with PV solar (179,500 Mg of Cu for each TW of electricity). In such a situation, our calculations can be adjusted accordingly. We do so as a part of our policy implications discussion below.

A final consideration regarding copper demand relates to copper's potential for substitution. In this regard, Graedel et al. (2015a, Supplementary Information) show that no suitable substitutes are available for copper's major uses. In any case, possible substitutes for copper would have to be produced at high volume due to the high production volume of copper; few potential substitutes could meet that requirement.

Considering the information above leads us to believe that our approach to future copper demand is reasonable.

Copper supply estimates are reasonably challenging, because fairly wide differences exist among geologists about the primary copper supply potential over long time periods; these involve geological modeling, information that is often proprietary, exploration prospects, reasonable mine depths, and so forth. This challenge has been addressed in the present work by evaluating total demand against a range of geological metrics (Figure 4), and by the realization that Northey et al. (2014) find that no qualitative changes in results occur even for resource changes of ±50%.

For secondary (recycled) resources, the supply hinges on end-of-life copper recycling rates. Glöser et al. (2013) estimate this poorly-defined value for copper at about 45%. We have chosen to utilize the maximum value that has been reached for the fraction of the supply that could be provided by secondary resources, a choice that leaves little room for major changes over time.

Finally, there is the issue of energy use per unit of copper produced. This is highly proprietary information on a company basis. We have employed data from a several-year old study of Australian copper mines (Norgate and Jahanshshi, 2010) which is probably reasonably representative of current practice. Going forward, one could anticipate a gradual improvement in energy efficiency, so we utilize a value of 30% for the energy saving in copper production, which is the midpoint among the estimates and predictions of the potential energy saving in the metal production sector.

Overall, we regard the results of this work as reasonable representations of the copper-related world that is envisioned by the scenarios.

3.6 Discussion on the sustainability implications of copper use

Copper is one of the most widely-used metals in society. Its demand is growing as a result of increasing demand for the services provided by copper-containing products. Consequently, there are several sustainability implications of copper use. Copper is widely employed to distribute energy in buildings, transportation, infrastructure, and electronics. As the overall income level is increasing worldwide, the number of people living in poverty is decreasing, and the number of people with access to improved drinking water and electricity is increasing, the demand for the services provided by copper containing applications is expected to keep increasing in view of their essential nature in the transition to a more sustainable society. The benefits of copper resources to society are not limited to copper itself, but also to other metals, mainly produced from copper resources, that are necessary for construction activities as well as for the transition to sustainable energy, transportation, and industrial systems. On the other side, the extraction and processing of copper ores are energy intensive, which will lead to an increase in the global environmental change as a result of CO_2 and other emissions unless the energy demanded for copper is provided by renewable technologies. It is also important to reduce the energy use in copper production either by increasing the recycling rate or by increasing the energy efficiency in copper's primary production. Although these options might lead to a reduction in the energy demand and consequently production cost, it is important to consider the rebound effect as the reduction in the cost could lead to an increase in the metal containing products demand and consequently the demand for the metal.

4. Policy Implications

Given the unpromising nature of these results, it seems appropriate to explore possible policy options in response to a copper supply challenge. First, enhancing copper supply could be achieved by locating and developing new copper deposits. This activity is already in progress by the mining industry, so the potential for a major revision of copper mineral resouces seems unlikely (note that a 50% resource change in the model of Northey et al. (2014) does not produce qualitative changes in long-term supply), although government encouragement of mineral research and exploration is likely to be of help. A second potential enhancement of supply is improving copper recycling rates. This again would be of some help, but with secondary copper curently providing less than 20% of total supply (Figure 1 (c)) a higher recycling rate would not make a major difference to supply. Third, any efficiency gains in the copper production chain (i.e. losses at the level of mining, smelting, refining, alloy fabrication, and product manufacture) would lead to a reduced demand for primary copper. A fourth possibility for enhancing copper supply could be the exploitation of unconventional copper sources. Seafloor deposits are a frequently-cited possibility in this regard, but seafloor copper supplies appear to be modest compared to terrestrial deposits (Hein et al., 2013; Molemaker et al., 2014), and the environmental consequences of seafloor mining provide a powerful constraint against extensive exploitation of seafloor resources (Van Dover, 2014; Wedding et al., 2015). An alternative sometimes suggested is the mining of asteroids (e.g., Keck Institute for Space Science, 2012). However, the technology for asteroid capture and mining is not developed, and there are no estimates of copper resources on asteroids. We conclude that it is unlikely that either of these unconventional resources will play a major role in copper supply in the next few decades.

Next, we turn to the possible policy initiatives related to copper demand. Perhaps the most obvious actions would seek to directly constrain individual aquisition of copper-containing products or of their use, as in failing to provide energy infrastructures or raising taxes to constrain income growth. Such actions would be widely unpopular, however, and thus politically challenging to implement.

A more promising action could be to encourage the redesign of copper-relevant technologies so as to minimize or avoid copper demand. As was pointed out above, direct metal-for-metal substitution is unlikely for the major copper uses: energy transport in buildings, transportation, infrastructure, and electronics. Assuming that energy provisioning will continue to be demanded, the situation calls for an economic and readily deployable conductor to be identified and developed. Such a conductor should not, of course, involve other metals whose long-term supply is thought to be problematic (European Commission, 2014; Graedel et al., 2015b). An obvious candidate in this regard could be graphene, which is an outstanding conductor of electricity, particularly in ribbon form (Gibney, 2014; Ciraminna et al., 2015). Although a widely-deployed transformative technology cannot be predicted, it seems not too unrealistic to imagine that graphene or one of its analogous materials (silicone [Davenport, 2015], molybdenum disulfide [Service, 2015]) may replace a significant portion of copper demand for electrical conduction over the next several decades.

To explore this idea, we have conducted an experiment in which we replace by 2050 some 30% of copper demand by one or more unspecified materials (perhaps plastics for plumbing and graphene for electrical wiring, for example (World Health Organization, 2006; Gibney, 2014)). This changes the picture so far as copper resources are concerned, of course. Figure 6 shows that under those conditions the Reserves are exhausted in all scenarios but the Reserve Base are exceeded only for the Equitability First scenario. A related consequence is that the supply of metals co-mined with copper (selenium, tellurium, arsenic, and small amounts of silver and gold;

Nassar et al., 2012, 2015) will decrease unless their extraction efficiencies from copper ore are substantially increased. This experiment illustrates the dependency of copper's future and those of its co-products to the evolution of copper supply and demand over the next several decades.

5 Conclusions

This study has developed four scenarios for the demand and supply of copper and the associated energy required for copper production. The scenarios are enhancements of the widely-used GEO-4 scenarios of the United Nations Environment Programme. The main conclusions of the analysis are

- The demand for copper is expected to increase by between 275-350% by 2050, depending on the scenario
- The highest demand for copper is expected to be in the Equitability First scenario and the lowest in the Security First scenario.
- The demand for copper in the four scenarios is expected to exceed the copper Reserves and Reserve Base estimates, as well as requiring almost the entire Ultimate Recoverable Copper resources by mid-century.
- Most of the copper producing countries will not be able to sustain their production until 2050, based on their current share of global copper production.
- The energy required to produce copper is expected to constitute between 1.0 and 2.4% of the total energy demand by 2050 for all sectors of society, compared to only 0.3% today..

It is clear from the analysis that the demand for copper in all scenarios is expected to increase and exceed the projected copper mineral resources by mid-century. The increase in copper demand will be associated with a strong increase in the demand for energy and consequently the environmental impacts.

Several policy options could reduce future copper-related impacts on society. These include, on the supply side, goverment encouragement of mineral research and exploration, and incentives for improving copper recycling rates. Although unconventional copper sources such as seafloor deposits and asteroids will not play a major role in copper supply in the near future, goverments should encourage consideration of these sources as a possible long term supply option. On the demand side, it is important to increase the efficiency of the copper cycle by minimizing losses at the level of mining, smelting, refining, alloy fabrication, and product manufacture, to minimize the use of copper in dissipative and unrecyclable applications, and to encourage the redesign of copper-relevant technologies. To minimize the impacts associated with copper production, it is important as well to increase the efficiency of energy use in the copper industry, to encourage the shift towards renewable technologies, and to maximize extraction efficiency of copper's companion metals (Te, Se, Ag, Co, and Mo), which are necessary for the transition to sutainable energy, transportation, and industrial systems.

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Box 1. Brief "storylines" of the UNEP GEO-4 foundational scenarios

Market First (MF). A market-driven world in which demographic, economic, environmental, and technological trends unfold without major surprise relative to currently unfolding trends.

Policy First (PF). A world in which strong actions are undertaken by governments in an attempt to reach specific social and environmental goals, especially as pertains to renewable energy.

Security First (SF). A world of great disparities where inequality and conflict prevail, brought about by socio-economic an environmental stresses.

Equitability First (EF). A world in which a new development paradigm emerges in response to the challenge of sustainability, supported by new, more equitable values and institutions

Figure Captions

Figure 1. (a) Copper use in different industrial sectors, 1980-2010 (USGS, various years; Spatari et al., 2005; Nassar et al., 2012); (b) The historical supply of copper from secondary sources; (c) The percentage contribution of secondary sources to total copper supply (ICSG, 2006, cited in Gomez et al., 2007; ICSG, 2012, 2015); (d) Copper historical production and resources by country or region (per cent of global total) (USGS, various years; Northey et al., 2014).

Figure 2. (a) The anticipated decrease of ore grade as a function of cumulative production (based on data from Mudd, 2013; Schodde, 2010; USGS, 2013) (b) The amount of energy as a function of ore grade required to produce a ton of copper by pyrometallurgy and hydrometallurgy (based on data from Norgate and Jahanshahi, 2010).

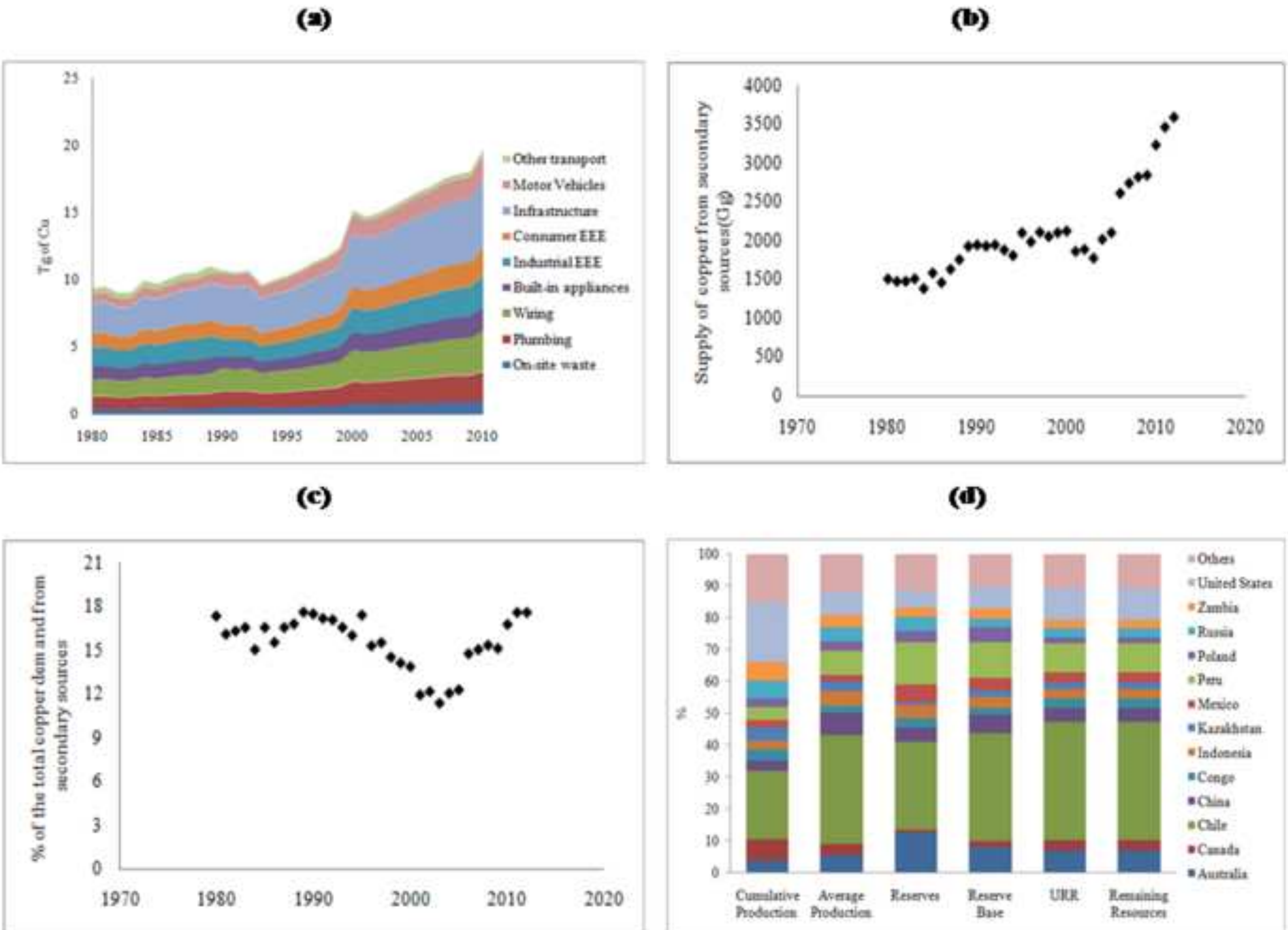
Figure 3. (a) Global copper demand for the four GEO-4 scenarios; (b) fractional uses of copper in 2010, 2025, and 2050 for the four GEO-4 scenarios; (c) the supply of copper from primary sources in the four scenarios; (d) The supply of copper from secondary resources in the four scenarios. The MF results are not visible, as they are essentially identical to those of PF and are obscured by the PF results.

Figure 4. Global cumulative copper production compared to Reserves, Reserve Base, Ultimate Recoverable Resources, and Remaining Resources. The vertical dashed lines indicate the years when specific scenarios surpass the copper Reserves and Reserve Base estimates. The color scheme is the same as for Figure 3.

Figure 5. (a) Cumulative copper production, historical (540 Tg from 1920 to 2010) and generated by the four scenarios, 2010-2050; (b) Copper ore grades mined, 2010-2050 under the four scenarios; (c) the energy required to produce copper by hydrometallurgy in the four scenarios, 2010-2050; (d) the energy required to produce copper by pyrometallurgy in the four scenarios, 2010-2050; (e) total energy required to produce copper in the four scenarios, 2010-2050. The dashed lines indicate the inclusion of energy efficiency improvements.

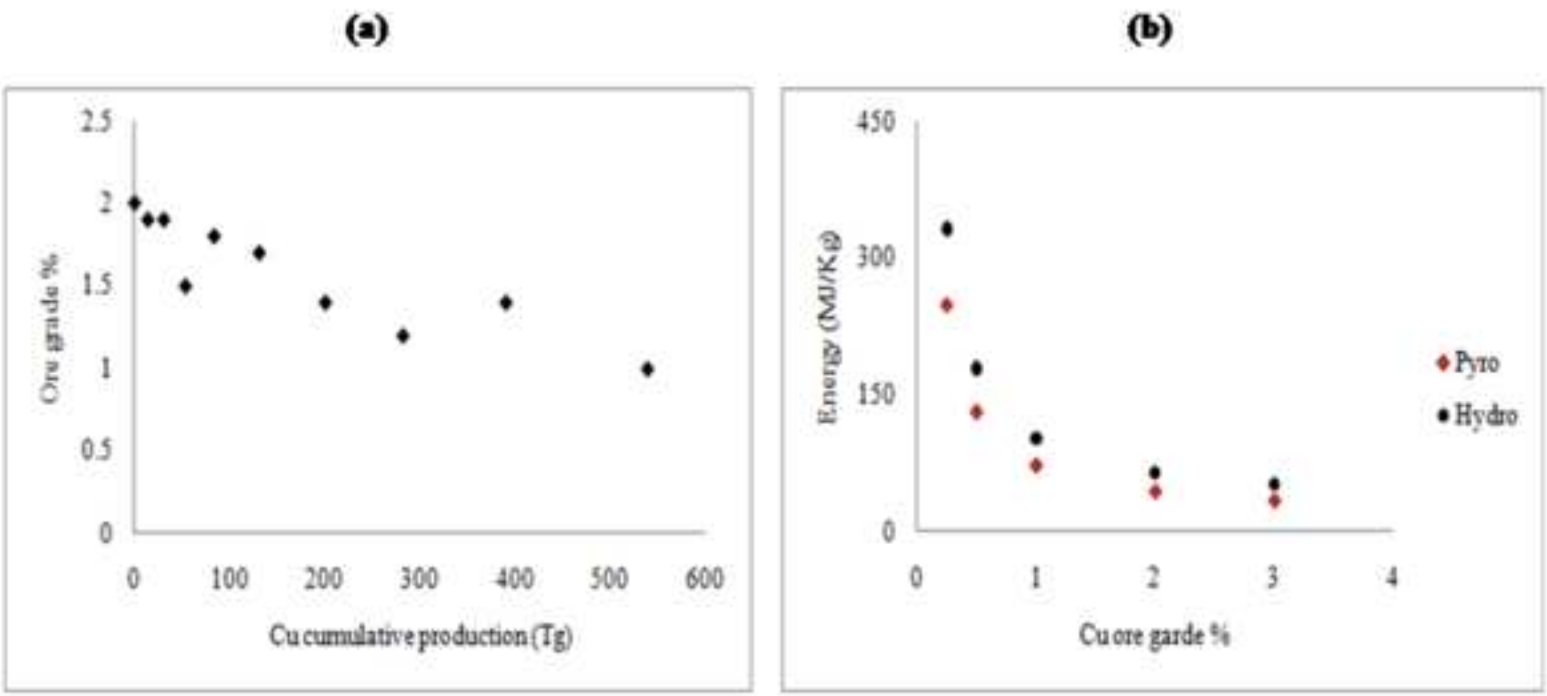
Figure 6. Global cumulative copper production compared to reserves, reserve base, ultimate recoverable resources, and remaining resources, for scenarios in which half the copper used to conduct electricity is replaced over the 2010-2050 time period by a non-metallic conductor. The vertical dashed lines indicate the years when specific scenarios surpass the copper Reserves and Reserve Base estimates. The color scheme is the same as for Figure 3.

Figure

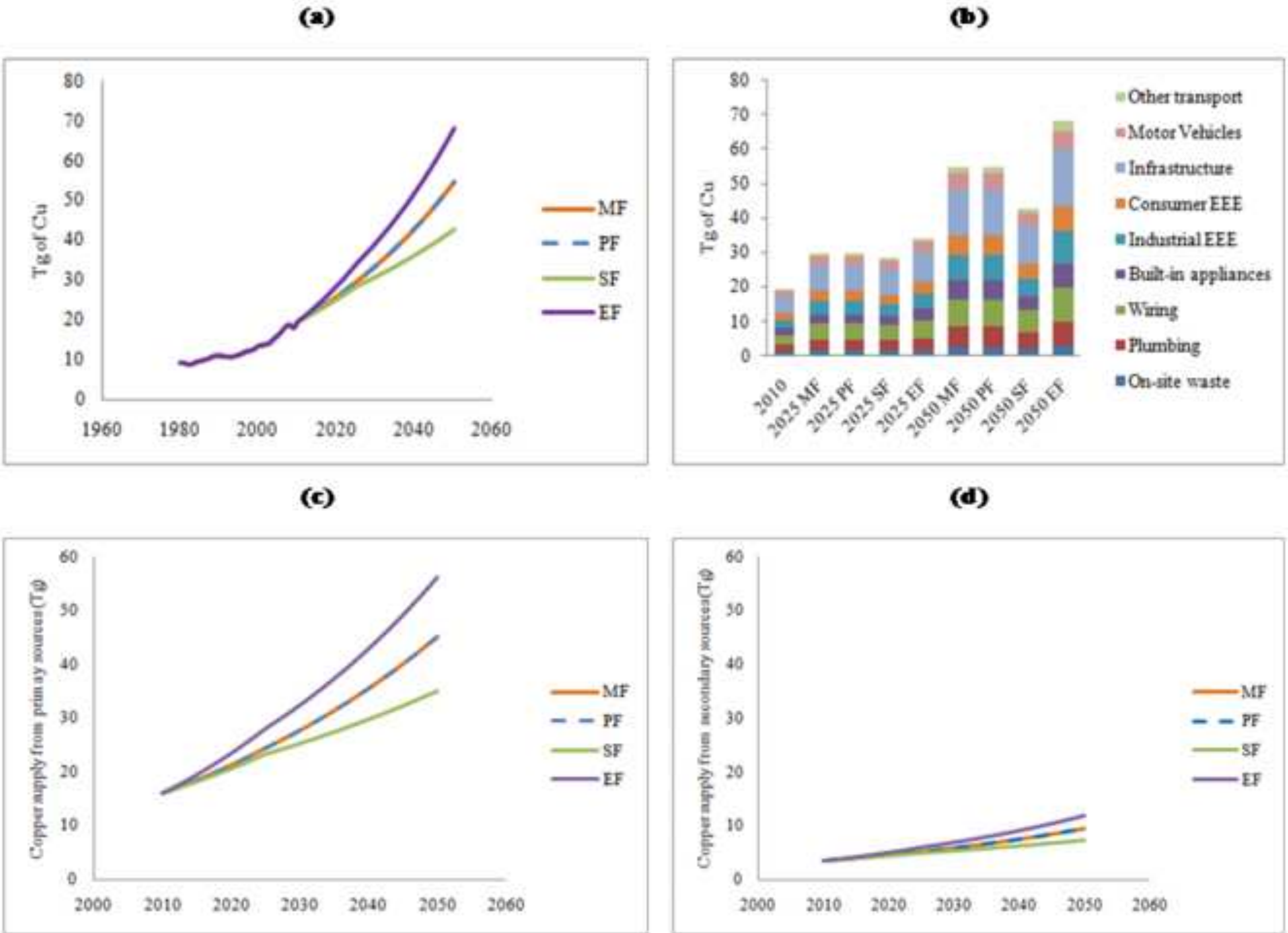


(a)
Tg of Cu
Other transport
Motor Vehicles
Infrastructure
Consumer EEE
Industrial EEE
Built-in appliances
Wiring
Plumbing
On-site waste
(b)
Supply of copper from secondary sources(Gg)
(c)
% of the total copper dem and from secondary sources
(d)
%
Others
United States
Zambia
Russia
Poland
Peru
Mexico
Kazakhstan
Indonesia
Congo
China
Chile
Canada
Australia
Cumulative Production
Average Production
Reserves
Reserve Base
URR
Remaining Resources

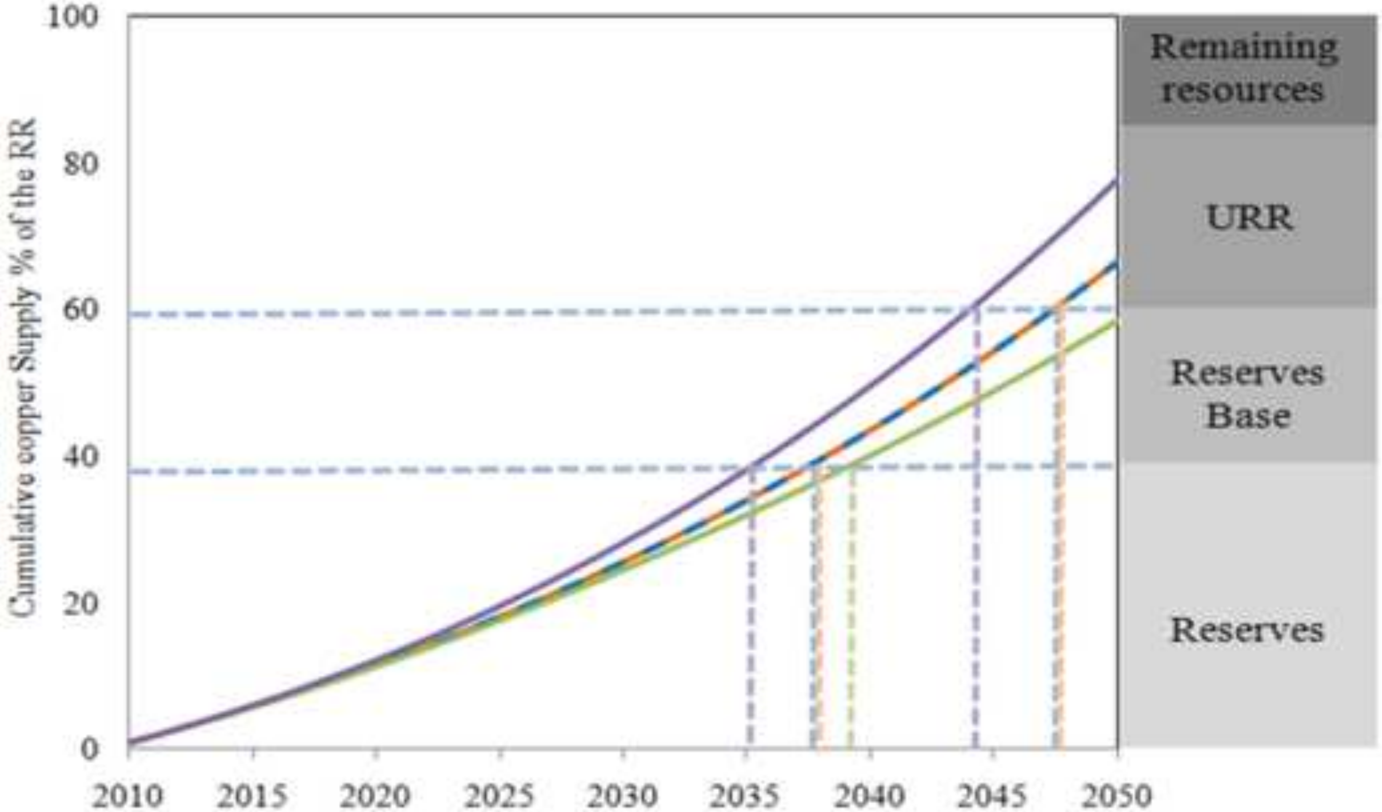
Figure


(a)
2.5
2
1.5
1
0.5
0
Ore grade %
0
100
200
300
400
500
600
Cu cumulative production (Tg)
(b)
450
300
150
0
Energy (MJ/Kg)
0
1
2
3
4
Cu ore garde %
Pyro
Hydro

Figure

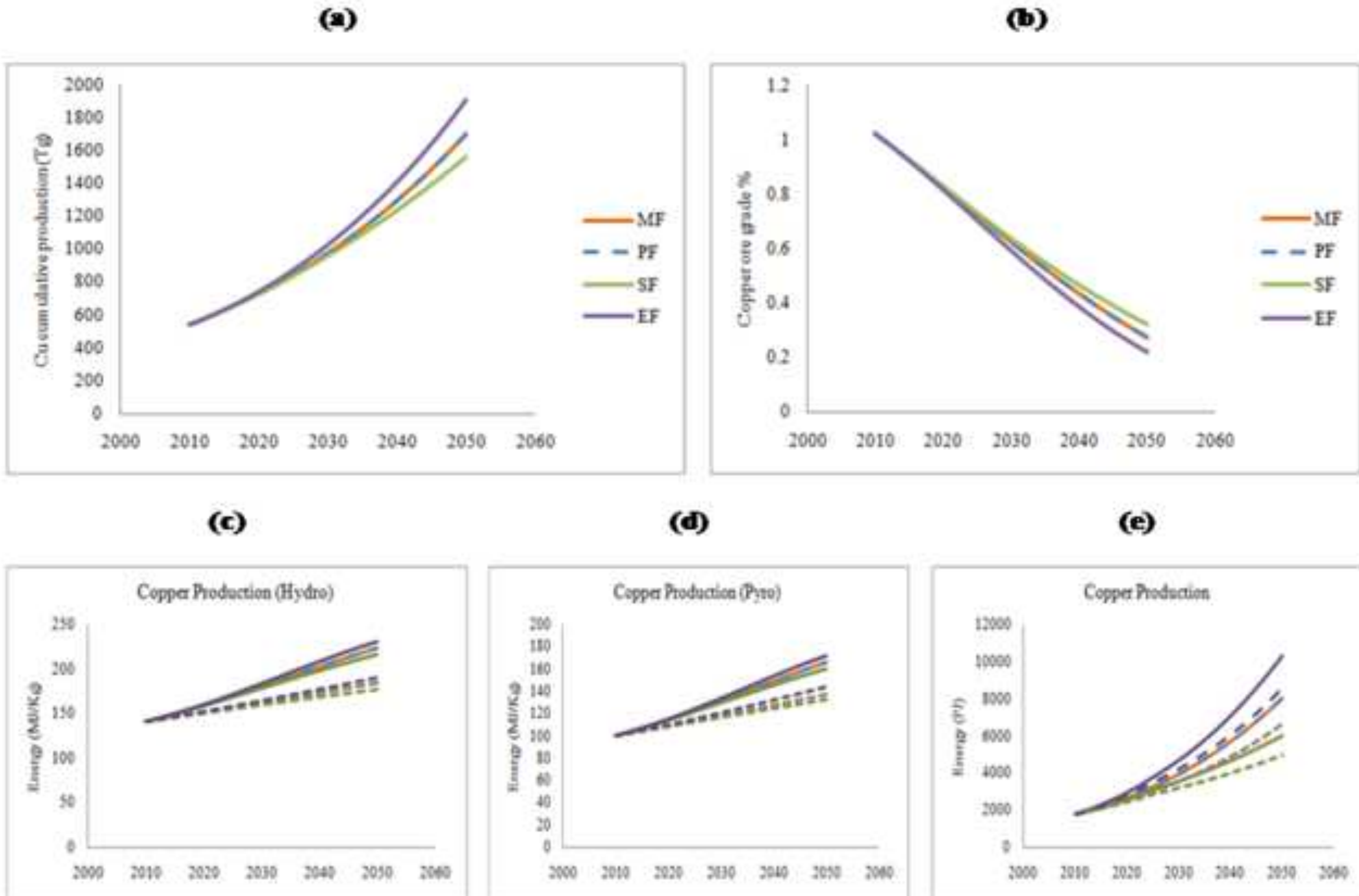

(a)
(b)
(c)
(d)
Tg of Cu
MF
PF
SF
EF
Other transport
Motor Vehicles
Infrastructure
Consumer EEE
Industrial EEE
Built-in appliances
Wiring
Plumbing
On-site waste
2010
2025 MF
2025 PF
2025 SF
2025 EF
2050 MF
2050 PF
2050 SF
2050 EF
Copper supply from primary sources(Tg)
Copper supply from secondary sources(Tg)

Figure

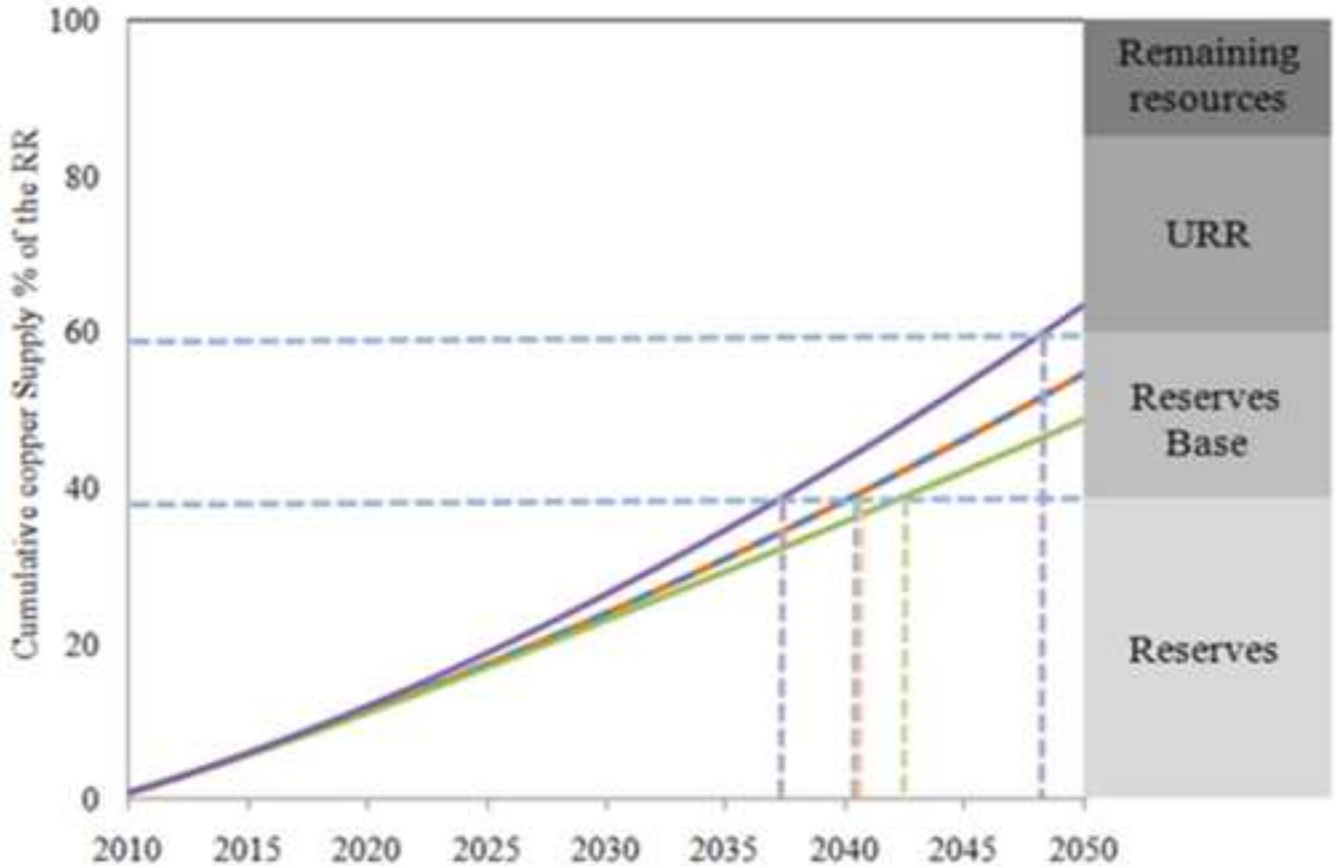


Cumulative copper Supply % of the RR
100
80
60
40
20
0
2010
2015
2020
2025
2030
2035
2040
2045
2050
Remaining resources
URR
Reserves Base
Reserves

Figure


(a)
(b)
Cu cumulative production (Tg)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2000
2010
2020
2030
2040
2050
2060
MF
PF
SF
EF
Copper ore grade %
1.2
1
0.8
0.6
0.4
0.2
0
(c)
(d)
(e)
Copper Production (Hydro)
Energy (MJ/Kg)
Copper Production (Pyro)
Copper Production
Energy (PJ)
12000
10000
8000
6000
4000
2000

Figure



100
80
60
40
20
0
Cumulative copper Supply % of the RR
2010
2015
2020
2025
2030
2035
2040
2045
2050
Remaining resources
URR
Reserves Base
Reserves